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Optical absorption and birefringence in GaAs/AlAs MQW structures due to intersubband electron transitions

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Abstract. For the first time the electrooptical phenomena due to intersubband electron transitions were investigated in GaAs/AlAs MQW structures. These structures are purposed for creation a mid infrared laser of new type. Experimental results on electron redistribution between size-quantization levels under electron heating were obtained up to electric field of 3500 V/cm.

Mid infrared (IR) semiconductor lasers ($\lambda = 4-15\ \mu$m) can find extensive applications in different fields. The development of physics and technology of low-dimensional structures opens up new possibilities of the development of mid IR lasers. Many attempts have been made to find structures with quantum wells in which an intraband population inversion between the size-quantization levels can be produced. Studies in this field have already resulted in the development of quantum cascade lasers [1] and fountain lasers with optical pumping [2]. However, a search for the new semiconductor lasers is still under way. Recently a new simple intraband laser scheme was proposed [3]. It is based on hot electron phenomena in GaAs/AlAs MQW structures under lateral transport, namely intervalley transfer and real space transfer of electrons. It should provide lasing in mid and far IR ranges. In the present paper an attempt of experimental study of electron redistribution between size-quantization levels under electron heating was taken. For the first time the electrooptical phenomena due to intersubband electron transitions were investigated in GaAs/AlAs MQW structures.

The structure under study was grown up by MBE method and consisted of 100 periods of 10 nm GaAs quantum wells and 2.5 nm AlAs barriers. The middle layer (5 nm width) of each quantum well was doped by Si ($N_D = 6 \times 10^{17}$ cm^{-3}). Low field electron mobility was about 1000 cm^2/V s at $T = 77$ K. Such small mobility (compared to MQW structures selectively doped in the barriers) points to significant electron scattering on impurities.

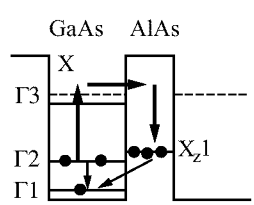

Fig. 1. Scheme of Γ–X transfer and electron accumulation in X subband under heating lateral electric field. Thin arrows denote radiative transitions.

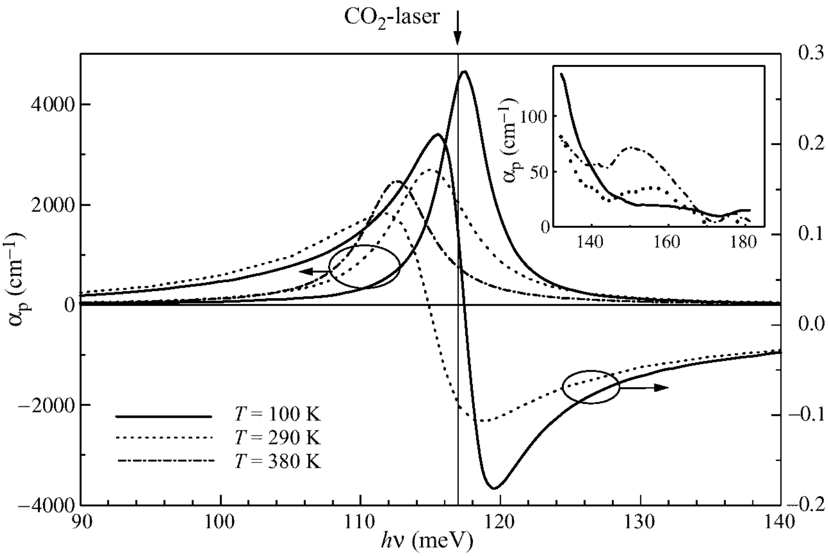

Fig. 2. Equilibrium absorption and birefringence spectra of GaAs/AlAs MQW structure at different temperatures. The experimental absorption spectra are restored taking into account the spectrometer resolution. The birefringence spectra are calculated with the help of Kramers–Kronig relations.

The considered MQW structure is such that the lowest electronic level of the system is the GaAs Γ-valley level, while the lowest level in the AlAs layer is the so-called X_Z-valley level (Fig. 1).

Energy distance between Γ1 and Γ2 levels is 117.4 meV at $T = 77$ K. Experimental absorption spectra demonstrate strong absorption peak due to Γ1−Γ2 transitions (Fig. 2). A weak peak near $h\nu \simeq 150$ meV is probably connected with optical transitions Γ2−Γ3. The intensity of this peak increases with the temperature due to the increase of the electron concentration in Γ2 subband.

In accordance with selection rules, Γ1−Γ2 optical transitions take place for light of p-polarization only. That is why there is a linear birefringence in the spectral range corresponding to these transitions, and refractive indexes for light waves of p- and s-polarization are not equal each other: $n_p \neq n_s$. We calculated the equilibrium spectra of birefringence magnitude $(n_p - n_s)$ with the help of Kramers–Kronig relationship and experimental spectra of optical absorption (α_p):

$$n_p - n_s = \frac{c}{\pi} \int \frac{\alpha_p(\omega')d\omega'}{\omega'^2 - \omega^2}. \tag{1}$$

The calculated equilibrium birefringence spectra are shown in Fig. 2. As it was predicted in [3], sufficiently strong lateral electric field can produce the electron population inversion between Γ2 and Γ1 levels, as well as between X_Z and Γ1 levels (Fig. 1). Electrooptical phenomena are convenient tools to study experimentally the electron redistribution between these levels. We investigated the modulation of optical absorption and birefringence in strong lateral electric field with the help of CO_2-laser. Its operating wavelength $\lambda = 10.6\,\mu$m is corresponding to the spectral range of Γ1−Γ2 intersubband transitions. To increase the sensitivity we used multipass waveguide geometry for the measurements, so that the total length of the optical way through the MQW layers was 17.7 μm. The

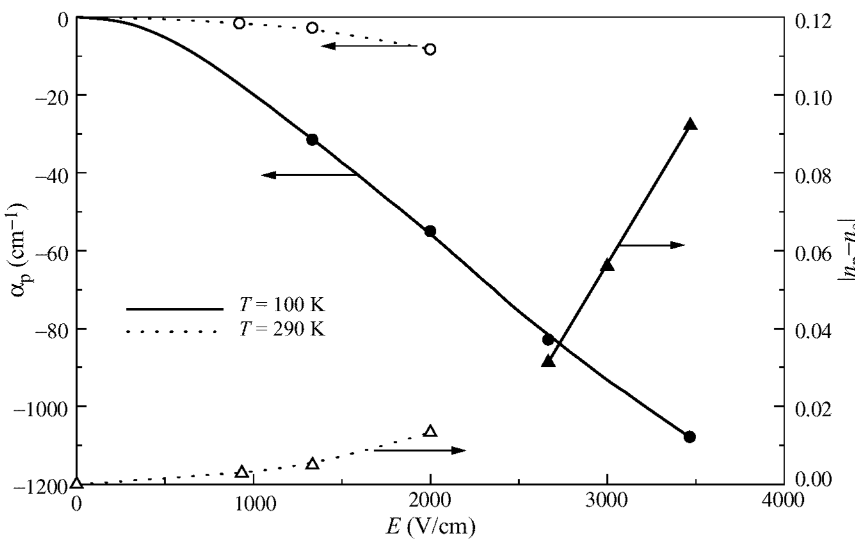

Fig. 3. Variation of the absorption coefficient and the birefringence magnitude with the lateral electric field.

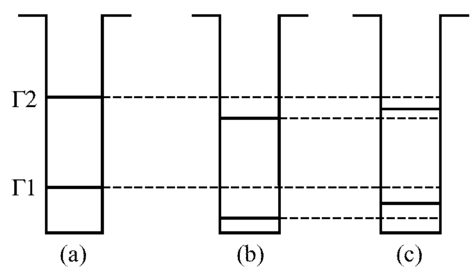

Fig. 4. Γ1 and Γ2 levels in quantum well without consideration of exchange interaction (a) and with it at different electron temperatures: low (b) and high (c).

incident laser beam excited the waves of both p- and s-polarization in the MQW layers. We measured the amplitude modulation as well as the modulation of phase retardation for these waves. Experimental technique was the same as it was described in [4]. Electron heating was achieved with pulse lateral electric field ($\Delta t = 200$ ns).

The results of electrooptical experiments are presented in Fig. 3. At a temperature of 100 K there is a great decrease of optical absorption in electric field of 3500 V/cm. The magnitude of decrease is $\Delta\alpha_p = -1100$ cm^{-1}, i.e. 25% of the equilibrium value of the absorption coefficient α_p. At the same field the magnitude of birefringence $\Delta\left|n_p - n_s\right|$ is about 0.1.

There are two reasons of the modulation observed. In addition to the redistribution of electrons between the size quantization levels, which we are interested in, we must also take into account the shift of the levels under electron heating due to exchange interaction effect. The role of exchange interaction in intersubband absorption was investigated in [5]. As one can see from Fig. 4, under electron heating the line of intersubband absorption undergoes a "red" shift due to exchange interaction effect.

As it is clear from Fig. 2, in the case of our experiment at $T = 100$ K and $\lambda = 10.6\,\mu$m the line shift gives a great contribution to birefringence modulation, whereas redistribution

of electrons between the size quantization levels gives a main contribution to absorption modulation. So we have extracted from our electrooptical measurements the value of spectral line shift and the rate of electron redistribution independently. At maximal electric field $E = 3500$ cm the magnitude of "red" shift is 0.7 meV, and relative decrease of difference $n_{\Gamma 1} - n_{\Gamma 2}$ is about 25%, where $n_{\Gamma 1}$ and $n_{\Gamma 2}$ are the electron concentrations in $\Gamma 1$ and $\Gamma 2$ subbands respectively. Similar value of "red" shift of absorption line can be estimated for investigated structure with the help of [5] and [6] taking into account relatively small electron mobility in our structure. The observed magnitude of $n_{\Gamma 1} - n_{\Gamma 2}$ is close to calculated one [3], so we can predict that population inversion between $\Gamma 1$ and $\Gamma 2$ subbands will appear at much higher fields: $E > 8$ kV/cm.

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